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Key Points:

- We address claim that neutrons from a 4 June 2011 event at Mercury are nonsolar
- The claim is based on an erroneous assumption about instrument singles counts
- The best interpretation of the neutron event is that the neutrons have a solar origin

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The 4 June 2011 neutron event at Mercury: A defense of the solar origin hypothesis

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Abstract We address the claim that an increase in the flux of neutrons detected by the Neutron Spectrometer (NS) on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft in orbit about Mercury at 15:45 UTC on 4 June 2011 was generated by the impact of energetic ions onto spacecraft. We find this claim to be unwarranted. The claim is grounded on the erroneous assumption that the NS singles count rate is triggered only by energetic ions. Rather, because any mix of energetic ions, electrons, photons, and neutrons can trigger NS singles, these data do not provide a reliable constraint on the presence of energetic ions. The absence of an enhancement in the count rate of 1635-keV gamma rays, as monitored by the MESSENGER Gamma-Ray Spectrometer, provides independent evidence that a fluence of energetic protons sufficiently high to generate the neutron enhancement was not present during the neutron event. The interpretation that currently best matches the available data is that the neutron enhancement on 4 June 2011 was the result of solar neutrons.

1. Introduction

NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft [*Solomon et al.*, 2007] operated at close solar distances (0.3 to 0.4 AU) between January 2008 and April 2015. This close proximity to the Sun, and the inclusion of a Neutron Spectrometer (NS) in the MESSENGER payload, provided the possibility of detecting low-energy (0.5–8 MeV) solar neutrons. Solar neutrons at these energies cannot be detected at Earth because free neutrons have an ~15 min mean life and therefore decay before reaching 1 AU. Detecting and characterizing low-energy neutrons can provide new insight regarding ion acceleration processes at the Sun [*Dorman*, 2010; *Vilmer et al.*, 2011]. To date, two studies have reported evidence for the detection of solar neutrons from MESSENGER NS observations [*Feldman et al.*, 2010; *Lawrence et al.*, 2014].

A key challenge for identifying solar neutrons with MESSENGER NS data is quantifying locally generated neutrons produced by the impact of energetic ions onto the spacecraft. Because the MESSENGER payload does not include instrumentation that can unambiguously characterize the species and energy of the charged-particle population for energies greater than a few MeV, several techniques have been employed to constrain our knowledge of the flux of energetic ions and the neutrons such ions can produce. These techniques include using NS charged-particle counters and independently measured gamma-ray data to constrain the maximum ion fluxes and energies and then using these ion constraints to model the maximum local neutron production on the spacecraft. With these techniques, *Lawrence et al.* [2014] showed that the measured neutron count rate during a neutron event on 4 June 2011 was 1–3 orders of magnitude larger than could be attributed to locally generated neutrons. On the basis, in part, of these results, *Lawrence et al.* [2014] concluded that there was strong evidence that the detected neutrons were solar in origin.

Share et al. [2015] (hereafter shortened to Share et al.) recently criticized *Lawrence et al.*'s [2014] study. In particular, Share et al. concluded that the excess neutrons detected on 4 June 2011 were generated locally at the spacecraft. Share et al. therefore contended that *Lawrence et al.* [2014] misidentified the 4 June 2011 neutrons as solar in origin. We respond to the four principal arguments offered by Share et al., and we show that their claim is unwarranted.

2. Response to Specific Arguments of Share et al.

Share et al. made four primary arguments to support their claim that the 4 June 2011 neutron event is the result of locally generated neutrons rather than solar neutrons. Before we respond to each of these arguments, we address an important misunderstanding that fundamentally affects the first three of their arguments. At the beginning of their discussion of the NS singles count rates, Share et al. stated, "These (singles) rates also have a peak… showing that there was a large flux of energetic ions at the time of the neutron transient." As argued in detail by *Feldman et al.* [2010] and *Lawrence et al.* [2014], however, the presence of an enhanced singles count rate does not establish the presence of energetic ions. The NS singles counters can be triggered by any combination of energetic ions, electrons, neutrons, and photons. In fact, enhanced singles count rates are regularly triggered by bremsstrahlung photons created by energetic electron events in Mercury's magnetosphere [*Ho et al*., 2011; *Lawrence et al*., 2015]. Because of this fundamental ambiguity, the NS singles counters cannot provide a reliable constraint on the presence of energetic ions. The assumption made by Share et al. that the large singles count rates show that "there was a large flux of energetic ions" is thus not valid. The first three arguments of Share et al. are undercut on this basis alone.

The first argument made by Share et al. is that the energetic particle environment at MESSENGER prior to the neutron event was similar to that at the Solar TErrestrial RElations Observatory (STEREO) A spacecraft after accounting for the difference in solar distance between the two spacecraft. Because the STEREO A spacecraft has instrumentation that can quantify energetic particle species and their energy for energies greater than a few MeV, such a comparison provided Share et al. increased confidence in the MESSENGER NS particle measurements, allowing them to "demonstrate that the neutron transient at 16:00 UTC was due to secondary neutrons produced by ion interactions in the spacecraft." To support this claim, Share et al. estimated that the singles count rate in the MESSENGER NS lithium glass 2 (LG2) sensor expected for energetic protons should be approximately 2500 counts per second (cps), a factor of only 2.5 greater than the measured LG2 count rate of 1000 cps.

This count rate estimate, however, was developed from several erroneous premises. First, the estimate was based on the assumption that LG2 singles are triggered entirely by protons, which as noted above is not a valid assumption. Second, Share et al. assumed a solid angle of 1 sr for the LG2 singles. However, this assumed solid angle was substantially underestimated, as the LG scintillators are planar detectors with a field of view of 2π sr. Third, on the basis of an analysis of two energetic electron events on 14 and 18 August 2010 by *Lario et al.* [2013], Share et al. assumed that the proton flux increases by a factor of 5 from 1 AU to 0.32 AU. However, as documented by *Lawrence et al.* [2014] (on the basis of a study by *Lario et al.* [2006] of energetic protons), a more appropriate distance-scaling factor at 0.32 AU is $1/0.32^2 \approx 10$. Thus, given Share et al.'s assumption that LG2 singles are due only to protons, the scaling given here shows that the LG2 count rate should be higher by a factor of 2π to 4π. The correctly estimated LG2 count rate for such energetic protons would then 15,000 to 30,000 cps, values that are 15 to 30 times higher than the measured count rate of 1000 cps. Thus, the singles counters cannot be used to support Share et al.'s claim that MESSENGER and STEREO A share a similar solar energetic proton environment. Moreover, the MESSENGER NS double coincidence count rates, which are less ambiguous than the singles count rates in identifying energetic ions and electrons, show that MESSENGER and STEREO A were not in similar energetic particle environments [*Lawrence et al*., 2014]. We note further that *Feldman et al.* [2010] validated the absolute calibration of the double coincidence count rates using quiet-time measurements of galactic cosmic rays. The energetic particle identification from the double coincidence count rates is thus well supported by independent calibration.

The second argument of Share et al. was that the estimated number of locally produced neutrons as derived from the LG2 singles count rate was comparable to the measured neutron count rate enhancement. Specifically, Share et al. estimated that the number of locally produced neutrons was 9 counts per second (cps), which is 30% smaller than the measured count rate of 13 cps (Share et al. quoted a measured count rate of 15 cps, but that value includes a 2 cps cosmic-ray background). However, the 9 cps value is likely a significant overestimate, for several reasons. First, Share et al. assumed that the entire LG2 singles count rate was due to energetic ions, which is almost certainly not the case during the neutron enhancement, as energetic electrons and photons will also contribute to the total singles count rate. Second, Share et al. assumed a neutron production on the basis of 20 MeV protons. However, if there was a fluence spectrum of 20 MeV protons sufficient to produce the large neutron enhancement, an extended proton spectrum that is distributed in energy as is normally observed during solar energetic particle events should trigger the NS double coincidence counter, which has a threshold only 10 MeV higher. As shown by *Lawrence* *et al.* [2014], there was no double coincidence enhancement during the 4 June 2011 event. Further, since the neutron production curve used by Share et al. (taken from *McKinney et al.* [2006]) is a steep function of energy, with lower-energy protons and alpha particles producing substantially fewer neutrons than higher-energy protons and alpha particles, the use of the singular 20 MeV value almost certainly yields a large overestimate. For these three reasons, we consider the neutron count rate of 9 cps for locally produced neutrons estimated by Share et al. to be unreliable.

The third argument of Share et al. was that *Lawrence et al.* [2014] did not provide a good explanation for the presence of the large singles count rates during the neutron event. This is a valid point, and *Lawrence et al.* [2014] acknowledged this issue by stating that "the large singles count rate during the neutron event is not fully understood." However, the presence of an enhanced singles count rate does not invalidate other evidence indicating an absence of an energetic-proton enhancement and locally generated neutrons. First, some portion of the singles count rates is likely to be the result of energetic electrons and photons generated by the interaction of neutrons with spacecraft material as well as the neutrons themselves. These particles will be present regardless of the source of the neutrons and therefore must be taken into account when attempting to understand the total singles count rate. Second, although Share et al. rightly asked why Mercury-originating neutrons did not generate an enhanced singles count rate similar to that seen during the neutron enhancement on 4 June 2011, one mitigating factor to note is that the energy spectra for neutrons from Mercury and solar neutrons need not be the same, especially for neutrons with energies greater than 8 MeV. Whereas the NS efficiently detects and positively identifies neutrons with energies less than 8 MeV, a solar spectrum can extend higher in energy, and such neutrons will more effectively generate energetic electrons and photons. In addition, the presence of beta-decay electrons and protons that accompany the neutrons cannot yet be ruled out as a contribution to the singles count rates.

Finally, for their fourth argument, Share et al. claimed that *Lawrence et al.* [2014] misinterpreted the MESSENGER gamma-ray data and therefore contended that these data do not prove that energetic protons were absent during the neutron enhancement. Specifically, Share et al. stated that *Lawrence et al.* [2014] "attributed all of the deexcitation lines… to inelastic neutron interactions and state that the line at 1.635 MeV can only be produced by proton interactions." Share et al. did point out an error in wording by *Lawrence et al.* [2014]. Specifically, we should have clarified the point that the 1635-keV line is not produced by $(n,n'\gamma)$ neutron inelastic reactions but rather from the decay of ^{23}Na, which is not present on the spacecraft at levels detectable by MESSENGER's Gamma-Ray Spectrometer (GRS) [*Peplowski et al.*, 2014]. Instead, this gamma ray is produced by the deexcitation of ^{23}Na produced by spallation processes on other spacecraft materials (e.g., Mg and Al) and therefore requires protons (and neutrons) of higher energies than those from $(n,n'\gamma)$ reactions. This point is shown in Figure 3 of Share et al., as illustrated by the markedly higher threshold energies for 1635-keV gamma-ray production relative to the other examples shown in that figure. It is the higher-energy thresholds for 1635-keV gamma-ray production that make the 1635-keV gamma ray well suited for constraining the particle environment at MESSENGER. We showed that the 1635-keV count rate did not increase during the neutron event, even though other lines with lower gamma ray production thresholds did show large enhancements (see Figures 1a and 10a of *Lawrence et al.* [2014]). This observation severely restricts the flux of protons (and neutrons) having energies $>$~20 MeV to levels below that detectable by the GRS via 1635-keV gamma-ray emission. The ~20 MeV cutoff is derived from the gamma ray production cross sections (Figure 3 of Share et al.).

Share et al. further presented a simulated gamma-ray spectrum that would be produced by spacecraft-like material in response to an increased flux of protons and alpha particles that follow a power-law energy spectrum. Share et al. stated that the "calculated photon spectrum using protons and alpha particles reproduced most of the features in the observed energy loss spectrum." We agree. One of the features this spectrum produces is the line at 1635 keV. Share et al. have therefore illustrated our point that for a plausible energetic ion spectrum, the 1635-keV line should show an enhancement. That no statistically significant 1635-keV enhancement above the cosmic-ray background was observed during the 4 June 2011 neutron event, despite the large enhancements seen in other gamma-ray peaks (Figure 1a), argues that a large fluence of energetic protons was not present at that time.

To demonstrate that some events do show an enhancement in the 1635-keV gamma-ray line, Figure 1b shows a solar particle event observed on 22 September 2011 when an increase of 2.3 ± 0.4 in the 1635-keV

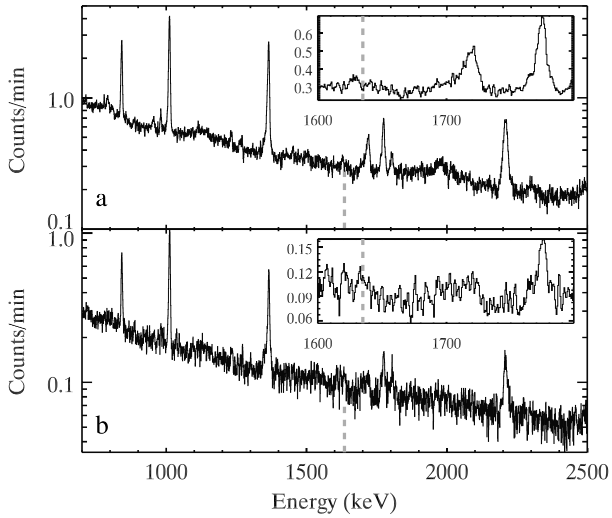

Figure 1. Locally generated gamma-ray fluxes observed by the MESSENGER GRS during the (a) 4 June 2011 and (b) 22 September 2011 events. Data represent difference spectra (before and during the enhanced particle events) derived from measurements acquired far from Mercury (altitudes >3000 km). Data were smoothed over 1.8 keV prior to subtraction, an interval that is approximately one-third the width of the gamma-ray peaks in this energy region. The dashed grey lines highlight the position of the 1635-keV peak. The insets highlight the 1635-keV region and show that this peak was enhanced by a value of 2.3 ± 0.4 relative to background during the 22 September 2011 event, but there was no statistically significant enhancement for the 4 June 2011 event.

line relative to the background count rate was observed. This measurement indicates the presence of protons with energies in excess of 20 MeV. We note that the energetic particle environment for the 22 September 2011 event differs from that for the 4 June 2011 event (Figure 2). The NS singles count rates (Figure 2a) are more than an order of magnitude smaller than the count rates for the 4 June 2011 event, whereas the double- and triple-coincidence counters show clear enhancements (Figure 2b), indicating that the 22 September 2011 event had a much harder energetic-particle spectrum than the 4 June 2011 event. The fast neutrons for the former event show a slight enhancement over background that reached a maximum at 1 cps around 18:00 UTC (Figure 2c). If we assume that all the coincidence count rates from the 22 September 2011 event are due to protons, we can use the modeled proton response of the double- and triple-coincidence counters [*Lawrence et al.*, 2014] and the measured coincidence count rates to estimate a spectral power-law index for this event. We find a power-law index of 2.2. This proton spectrum may then be used to estimate the ratio of measured to locally generated neutrons following the formulation given by *Lawrence et al.* [2014]. We determine this ratio to be 1.5, which is significantly smaller than the values of 2.7–5.4 obtained for the 31 December 2007 event [*Feldman et al.*, 2010; *Lawrence et al.*, 2014] and >500 obtained for the 4 June 2011 event [*Lawrence et al.*, 2014]. Thus, for 22 September 2011, there is a much higher likelihood that the detected neutrons were locally generated than for the other reported neutron enhancements. This event thus supports the idea that the presence or absence of the 1635-keV gamma-ray line indicates the presence or absence of energetic protons and further validates our model estimates of local neutron production.

The lack of an increase in the 1635-keV count rate during the 4 June 2011 event places strong constraints on whether a population of energetic protons (or neutrons) having energies greater than 20 MeV was present. This upper limit restricts the allowed population of protons capable of producing local neutrons via spallation processes [e.g., *Filges and Goldenbaum*, 2009] to those with energies of 5 MeV to 20 MeV. The lower limit is derived from the Coulomb barrier for the types of light nuclei present in the MESSENGER spacecraft, which ranges from ~5 MeV (C, atomic number $Z = 6$) to ~12 MeV (Al, $Z = 13$). Heavier nuclei, such as Fe and Ti, have enhanced neutron production via spallation, but their Coulomb barriers for protons are above the 20 MeV threshold established by the 1635-keV gamma ray. In either case, for protons <20 MeV, neutron production via spallation occurs via single neutron emission during the evaporation of compound nuclei. Compound nucleus formation is inhibited for light nuclei [*Krane*, 1998] for which <20 MeV protons are above the Coulomb barrier. Regardless, this neutron production mechanism is taken into account in our simulations of particle transport through the MESSENGER spacecraft. For these energies, neutron production per incident particle is highly inefficient, with a value of ~0.01 neutrons per incident proton [*McKinney et al.*, 2006].

Direct reactions (e.g., protons or alpha particles on ^{13}C) offer an alternative source of neutrons from compound nucleus evaporation. Local neutrons from these reactions were treated by *Lawrence et al.* [2014] in response to a prior critique by *Share et al.* [2011]. Our models, which included the specific cross

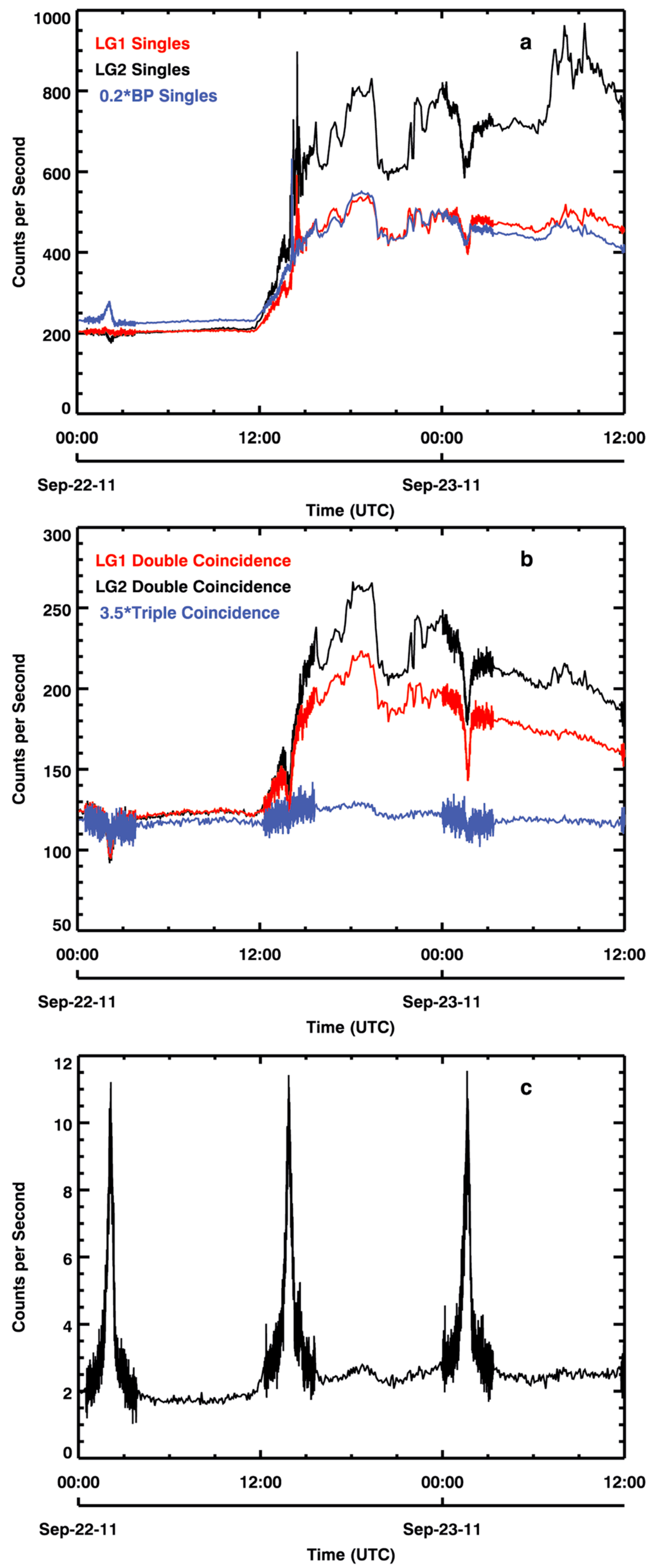

Figure 2. NS count rate data for (a) singles counters, (b) coincidence counters, and (c) fast neutrons during the 22 September 2011 neutron event. For the singles and coincidence counters, LG1 data are shown in red traces and LG2 data are shown in black traces. Borated plastic singles count rates, shown as the blue trace in Figure 2a, are multiplied by 0.2 to be seen on the same scale as the LG singles. Triple coincidence count rates, shown as the blue trace in Figure 2b, are multiplied by 3.5 to be seen on the same scale as the double coincidence count rates. The three fast-neutron count-rate peaks at rates greater than 10 cps denote neutron detections from Mercury periapsis passes and are not related to the solar particle event.

sections [*Koning and Rochman*, 2012] recommended by *Share et al.* [2011], considered incident particle energies of 10 MeV or greater. Our models show that neutron production for lower ion energies is negligible, consistent with the general behavior of total nonelastic cross sections [*Barashenkov*, 1993; *Carlson*, 1996]. These observations reinforce our conclusion that local neutrons cannot account for the observed neutron enhancement, and as a consequence, the best explanation for the neutrons detected on 4 June 2011 continues to be that they are nonlocal in origin and most likely solar.

3. Summary

We conclude that the claim of *Share et al.* [2015] that *Lawrence et al.* [2014] misidentified solar neutrons is unwarranted. Specifically, Share et al. grounded multiple arguments on the invalid assumption that only energetic protons trigger NS singles count rates. Second, Share et al.'s estimate of the energetic proton population prior to the neutron enhancement is inaccurate, and their estimate of local neutron production from the LG2 singles count rate is unreliable. Finally, their own simulated gamma-ray spectrum supports the contention that energetic protons with energies >20 MeV were absent during the neutron enhancement. There is therefore strong evidence that the neutrons detected from 15:45 UTC to 16:45 UTC on 4 June 2011 were solar in origin. We acknowledge that not all data taken during the neutron enhancement, especially the NS singles count rates, are understood. Further modeling of the NS instrument response and data analysis for the 4 June 2011 event and other events is therefore needed.

Share et al. concluded their analysis by describing a type of directional neutron measurement that would enable future measurements to make less ambiguous identifications of solar neutrons. A simpler approach that requires fewer spacecraft resources—particularly important for resource-constrained inner heliosphere missions—would be to use a simple neutron detector coupled with the type of energetic particle detectors used on the STEREO and Solar Probe Plus (SPP) missions [*von Rosenvinge et al*., 2008; *McComas et al*., 2015]. The capability to model energetic-ion-initiated neutron production and transport is sufficiently mature that as long as the spectrum of the incoming energetic ion flux is known, modeled absolute neutron count rate uncertainties should be less than 20% [*McKinney et al*., 2006; *Lawrence et al*., 2006], and relative neutron count rate uncertainties should be less than 0.5% for a variety of spacecraft locations and orientations with respect to an incoming directional flux [*Lawrence et al*., 2013]. The MESSENGER payload was constrained by mass and cost limits and was, of course, selected on the basis of planetary science objectives [*Solomon et al*., 2007]. Nonetheless, had MESSENGER been equipped with the type of energetic particle detectors that are on STEREO and will fly on SPP, the ambiguities associated with the neutron measurements of *Feldman et al.* [2010] and *Lawrence et al.* [2014] would have been resolved long ago.

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